Why We Study Binary Stars

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Some Introductory Comments

Just to make sure….Binary stars are systems of two stars gravitationally bound in mutual Keplerian orbits around a common center of gravity such that $M_1/M_2 = r_2/r_1$

Ptolemy (2 C AD) was the first to assign the designation $\delta\iota\pi\lambda o\upsilon\sigma$ incorrectly, it turns out, to ν^1 and ν^2 Sgr, without mentioning, for example, Alcor and Mizar as a pair

Earliest telescopic observers considered binaries to be accidental alignments offering the possibility of detecting stellar parallax

Physical separations range from stars in contact to those separated by hundreds of AUs

Stable multiple systems are configured hiearchically, i.e. can be approximately treated as nested binary systems

Significance of Binary Stars

Provide our only means of measuring stellar mass, the critical stellar evolutionary parameter (Vogt's Theorem)

The majority of stars exist in binary and multiple star systems

Exhibit many interesting phenomena – winds, disks mass exchange, etc.

Coeval origin of components permits studying evolutionary effects

Observational Classification

Superficially classified according to discovery technique:

VISUAL BINARIES – Direct resolution of individual components using eye, photography, interferometry, photoelectric scanning, AO, … "astrometric" binaries are a special subclass

SPECTROSCOPIC BINARIES – Detected as a result of variable radial velocity

PHOTOMETRIC BINARIES – Detected as a result of eclipsed induced variable brightness

A.H. Batten once noted that the above scheme "is very useful for distinguishing the astronomers who study binary stars, but it has few other merits."

Other Types of Binaries

"Astrometric Binaries" **– Detected by non-linear proper motion paths or quasi-sinusoidal variations from orbital motions (gives complete visual elements except for photocentric semi-major axis)**

"Occultation Binaries" **– Detected by stepwise nature of diffraction from lunar limb (measures vector separation)**

"Spectrum Binaries" **– Detected by presence of two or more discordant (no orbital information given, although have often been followed up by other techniques)**

"Common Proper Motion Binaries" **– Pairs of widely separated stars exhibiting similar proper motion (There are lots and lots of these!)**

Physical Classifications

Evolutionary Scheme of Sahade:

Type i – At least one component is pre-main sequence

Type ii – Both are main sequence
- *a. Similar spectral types*
- *b. Dissimilar spectral types*

Type iii – One component MS, other is class III or IV

Type iv – Both are III or IV
- *a. Similar spectral types*
- *b. Dissimilar spectral types*

Type v – One component below MS

Interactive Scheme of Kopal:

Detached – Neither component fills its Roche lobe

Semi-Detached – One component fills its Roche lobe

Contact – Both components fills their Roche lobe

A "Close Binary" is one in which one component, at some time or another, affects the evolution of the other.

Binary Star Statistics I.

VISUAL BINARIES – ~80,000 discovered to date (some are "optical" pairs) and ~1,000 orbits of which ~300 are of "good" or better quality.

SPECTROSCOPIC BINARIES – ~1,500 with orbits and another 1,000 or so with established velocity variations.

PHOTOMETRIC BINARIES – ~4,000 have been catalogued but <500 have detailed light curve solutions.

Binary Star Statistics II.

IN A SAMPLE OF 100 STARS, THERE ARE (following W.D. Heintz):

30 Single Stars (30)

47 Double Stars (94)

23 Multiple Stars (81)

Therefore, 100 "stars" yields 205 components or 85% of all stars are in systems.

So, watch out, chances are the "star" you're studying has a companion!

Binary Star Statistics III.

IN A SAMPLE OF 100 BINARIES, SEMI-MAJOR AXES ARE DISTRIBUTED AS (again, following W.D. Heintz):

8 pairs with $0.01 < a < 0.1$ AU

12 pairs with $0.1 < a < 1$ AU

20 pairs with $1 < a < 10$ AU

30 pairs with $10 < a < 100$ AU

24 pairs with $100 < a < 1000$ AU

6 pairs with $a > 1000$ AU

Visual Binaries

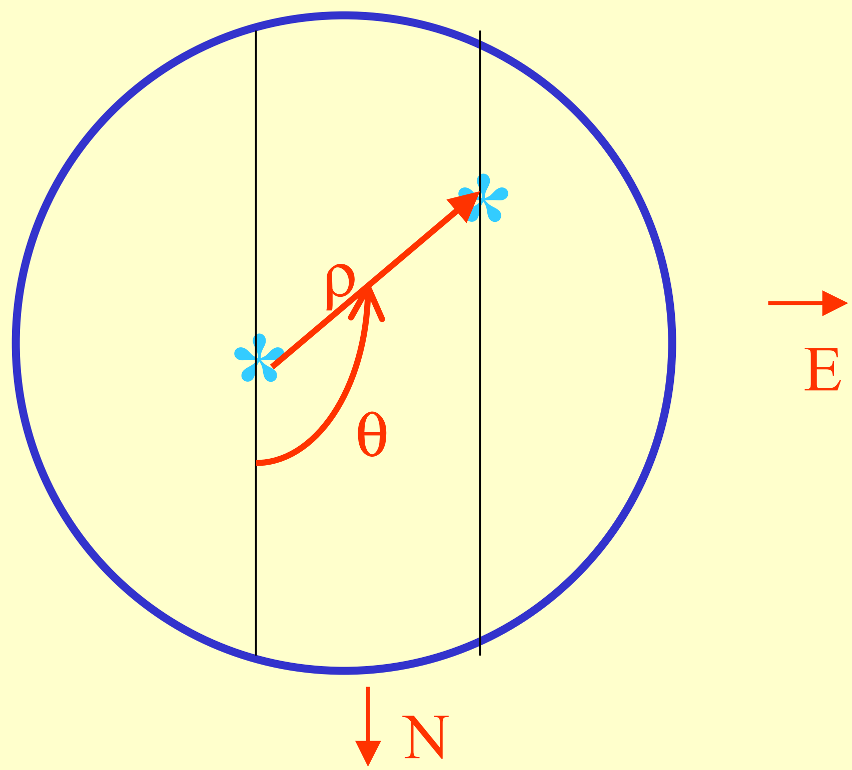
Traditionally resolved by the human eye with relative orbital motion measured by a "bifilar micrometer"

Basic observational data are:

Position Angle θ

Angular Separation ρ

Epoch of Observation t



Orbital Elements for Visual Binaries

Orbital Period **P** *– in years*

Epoch of Periastron **T** *–*
in Besselian Year

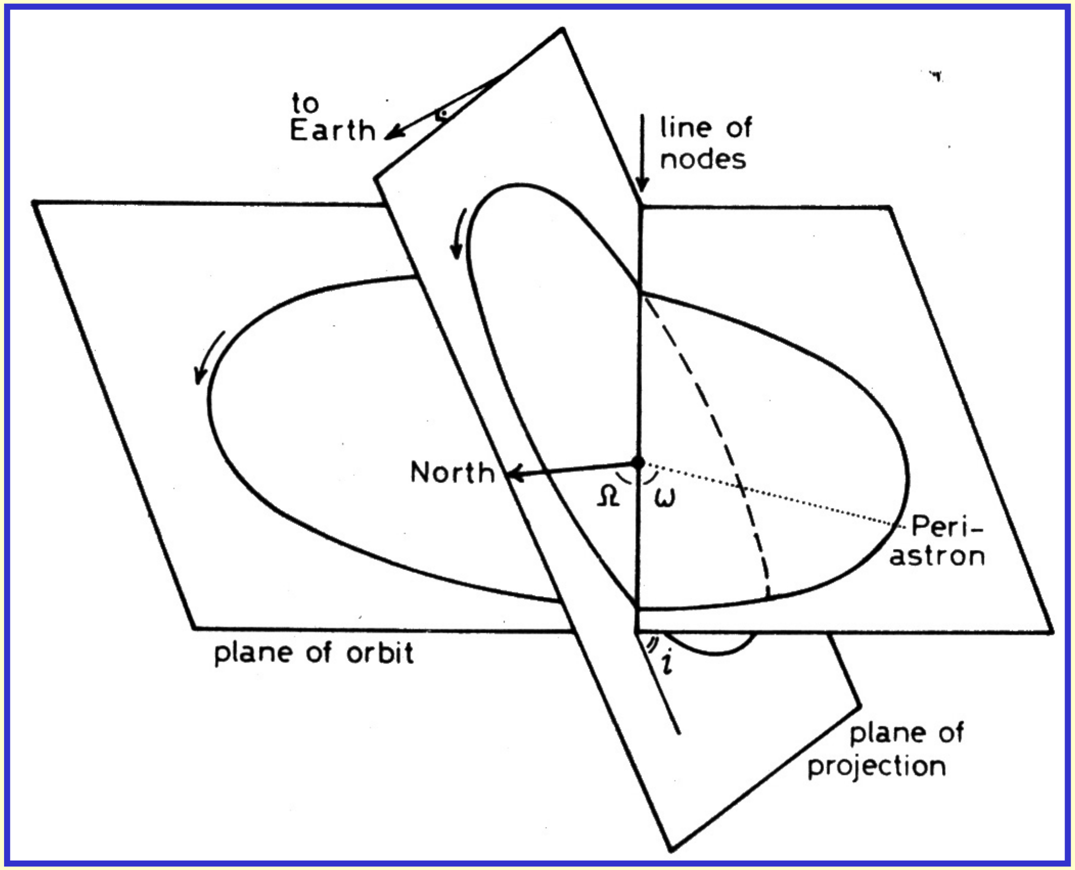
Semi-major Axis **a** *– in degrees*

Inclination **i** *– in degrees*

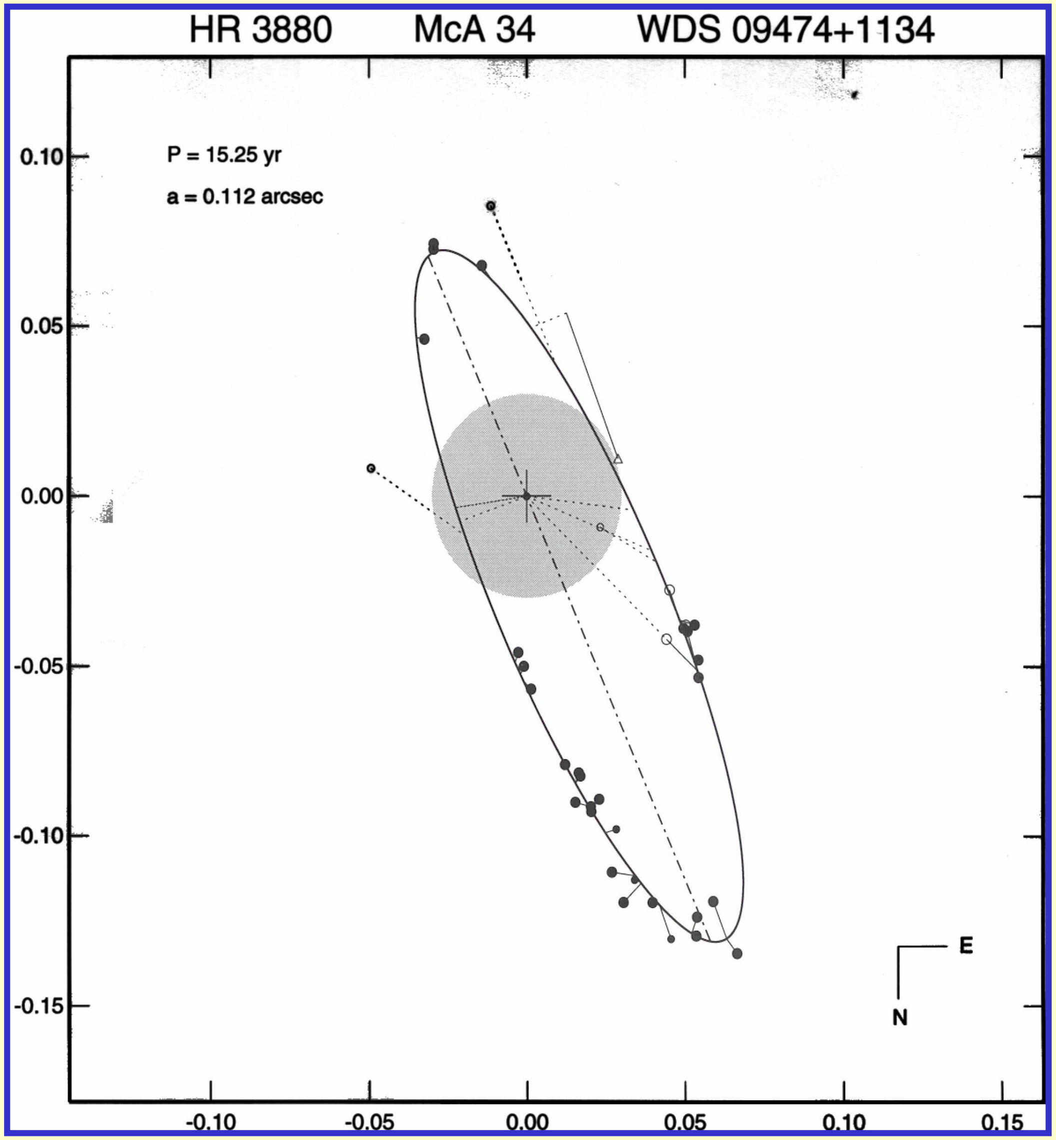
Eccentricity **e** *– fractional*

Periastron Longitude **ω** *–*
in degrees

Nodal Longitude **Ω** *–*
in degrees



Example Visual Orbit



Spectroscopic Binaries

Basic observational data are:

For a "single-lined spectroscopic binary" **SB1**
Radial Velocity of Primary V_1 and Epoch of Observation t

For a "double-lined spectroscopic binary" **SB2**
Radial Velocity of Primary V_1, Radial Velocity of Primary V_2 and Epoch of Observation t

Orbital Elements for Spectroscopic Binaries

Orbital Period **P** *– in days*

Epoch of Periastron **T** *– in Julian date*

Eccentricity **e** *– fractional*

Periastron Longitude ω *– in degrees*

Barycentric Velocity γ *or* V_o *– in km/sec*

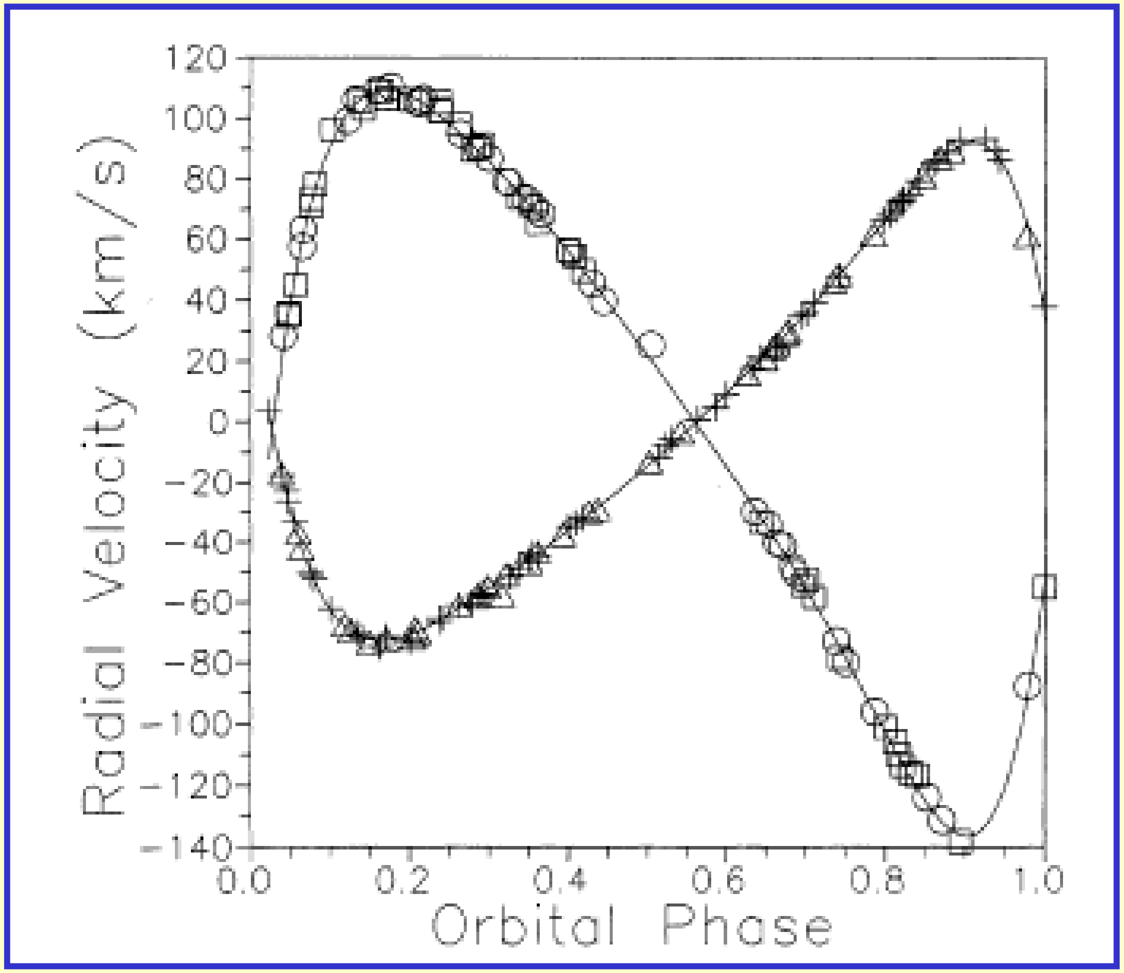
Primary Velocity Amplitude K_1 *– in km/sec*

Secondary Velocity Amplitude K_2 *– in km/sec*

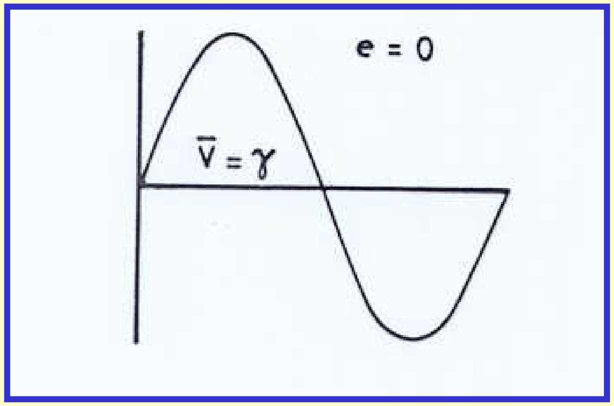
If you're lucky enough to detect the secondary!

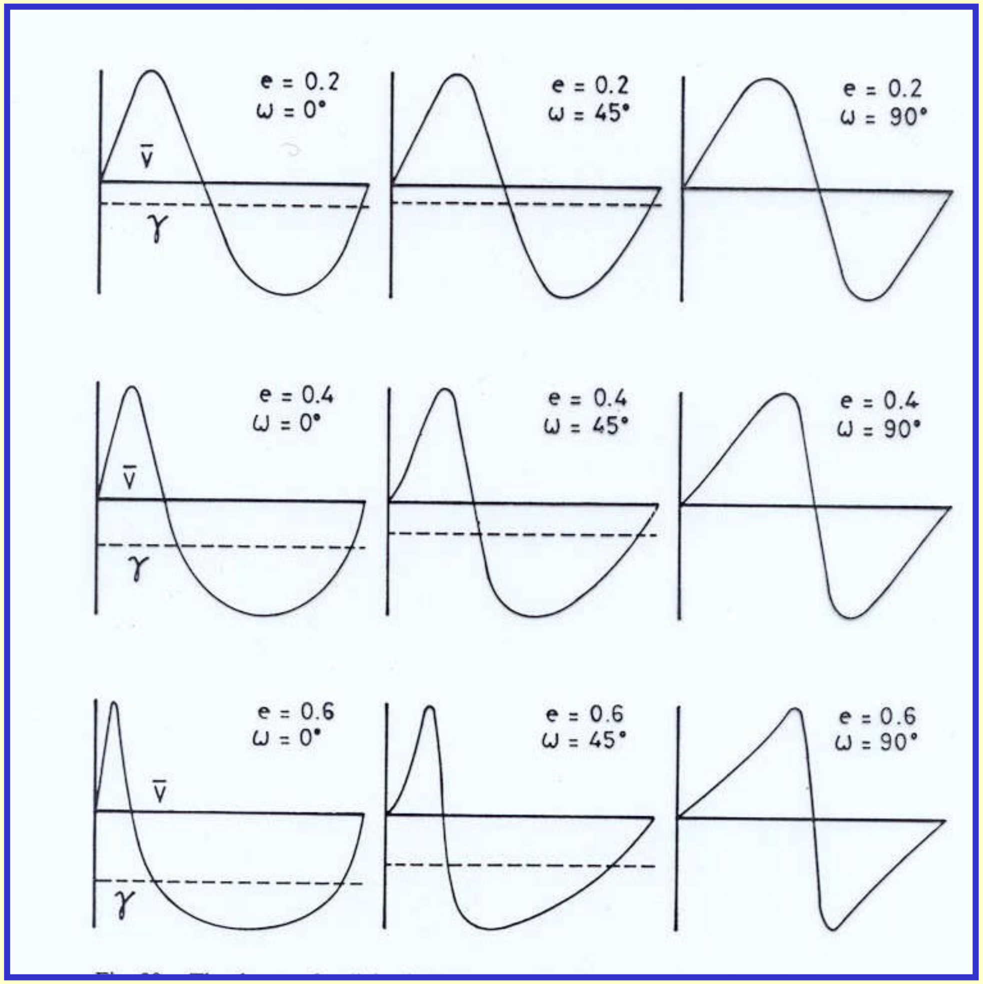
Example Spectroscopic Orbit – HR 266

Cole *et al.* AJ, 103, 1357, 1992

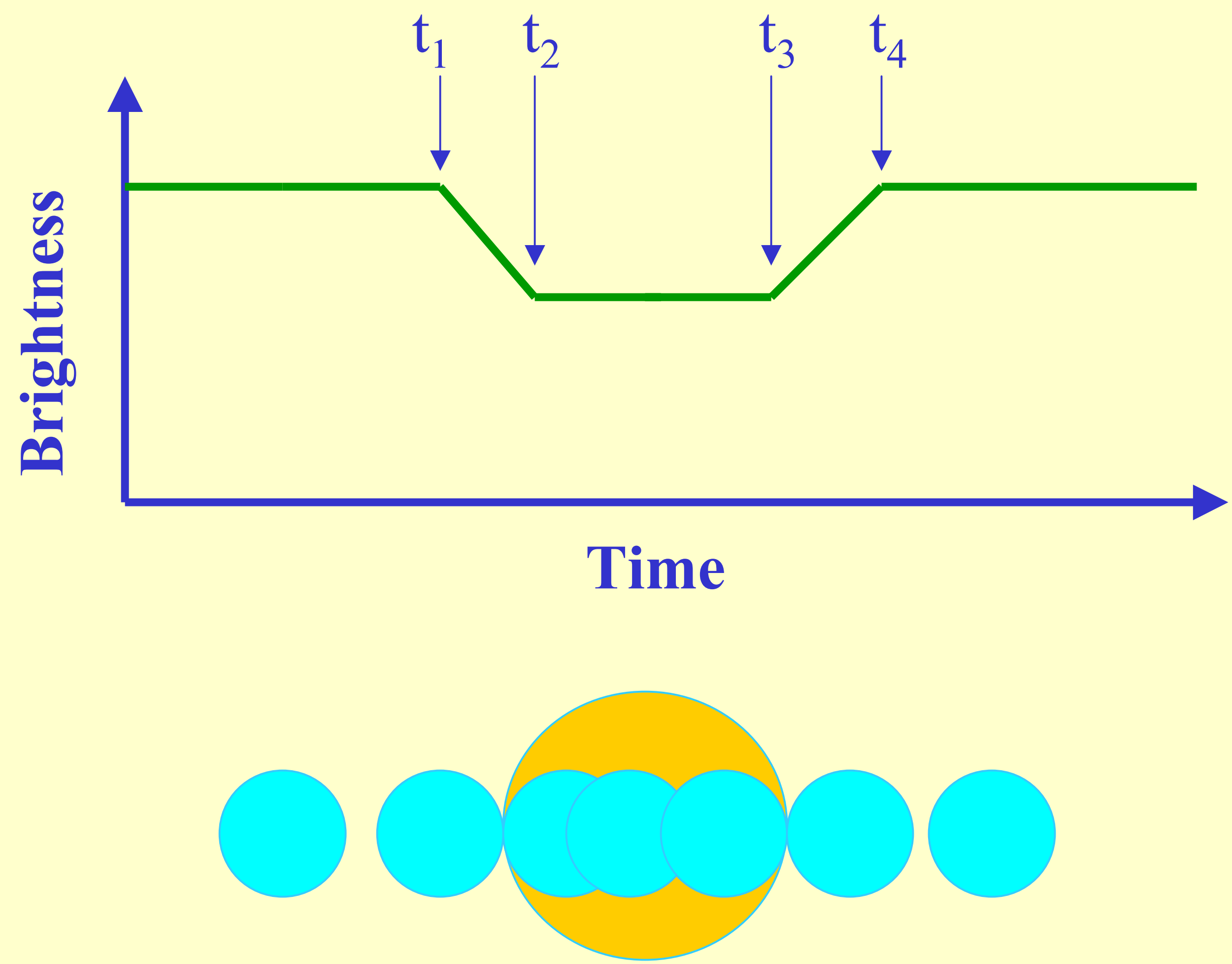


Radial Velocity Curve Sensitivity to *e* and ω

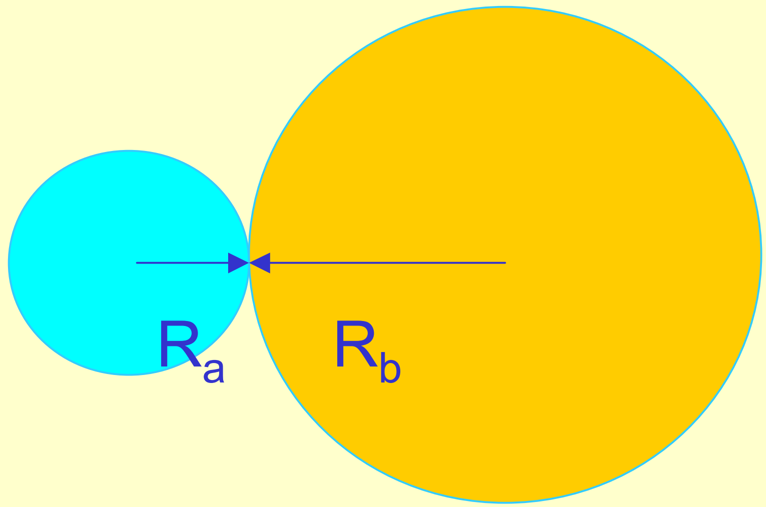




Photometric (Eclipsing) Binaries
(The ASTR 101 Version)



Simple Relations for Photometric Binaries



With:
P = Period
a = Semi-major axis

$$(t_2 - t_1)/P = (t_4 - t_3)/P = 2\,R_a/2\pi a$$

and

$$(t_3 - t_2)/P = 2\,R_b/2\pi a$$

Selection Effects & Discovery Probabilities

VISUAL BINARIES:

$$P = f\,(\,m_t,\ \Delta m,\ \rho\,)\ =\ f'\,(\pi)$$

nearby, long-period systems are favored

SPECTROSCOPIC BINARIES:

$$P = f\,(\,m_t,\ \Delta m,\ i,\ K\,)$$

Δm determines if SB1 or SB2

large K is favored by short period

PHOTOMETRIC BINARIES:

$$P = f\,(\,m_t,\ i,\ P\,)$$

inclination must be near 90 degrees

Kepler's Third Law

$$M_1 + M_2 = a^3 / P^2$$

Mass Sum is in solar mass units
if a is in AU and P is in years

Regrettably, no single observational technique directly measures a!

Mass ratio is required to produce Individual masses

$M_1 / M_2 = K_2/K_1$ for SB2s or a_2/a_1 for astrometric binaries

Mass Relations for Spectroscopic Binaries

$$a_{1,2} \sin i \text{ (km)} = 13{,}751\, K_{1,2}\, P\, (1-e^2)^{1/2}$$

$$M_{1,2} \sin^3 i \text{ (solar units)} =$$

$$1.036\times10^{-7}\, (K_1 + K_2)^2\, K_{2,1}\, P\, (1-e^2)^{3/2}$$

And

$$M_2 / M_1 = K_1 / K_2 \qquad \text{(for SB2)}$$

$$f(M)_{1,2} \sin^3 i \text{ (solar units)} = (M_2 \sin i)^3\, (M_1 + M_2)^{-2}$$

$$1.036\times10^{-7}\, K_1^{\,3}\, P\, (1-e^2)^{3/2}$$

(for SB1)

Obtainable Parameters

	P	T	a	e	I	ω	Ω	M_1	M_2	R_1	R_2	L_1	L_2	U_1	U_2	$Shape_1$	$Shape_2$
VB	yes	yes	a"	yes	yes	yes	yes	requires	distance	no	no	no	no	no	no	no	no
								& mass	ratio								
SB1	yes	yes	a1Sini	yes	no	yes	no	mass	function	no	no	no	no	no	no	no	no
SB2	yes	yes	aSini	yes	no	yes	no	x Sin3i	x Sin3i	no	no	no	no	no	no	no	no
PB	yes	yes	no	yes	no	~yes	no	no	no	r1=R1/a	r2=R2/a	yes	yes	~yes	~yes	~yes	~yes

Pathways to Mass Determinations

VISUAL ORBIT + PARALLAX + MASS RATIO FROM ASTROMETRY
Yields M_1, M_2, L_1, and L_2

Classical astrometric approach typically limited to later type binaries (and few and far between!)

SB2 ORBIT + INCLINATION FROM ECLIPSING SOLUTION
Yields M_1, M_2, R_1, R_2, L_1, and L_2

Very productive, especially for early type binaries

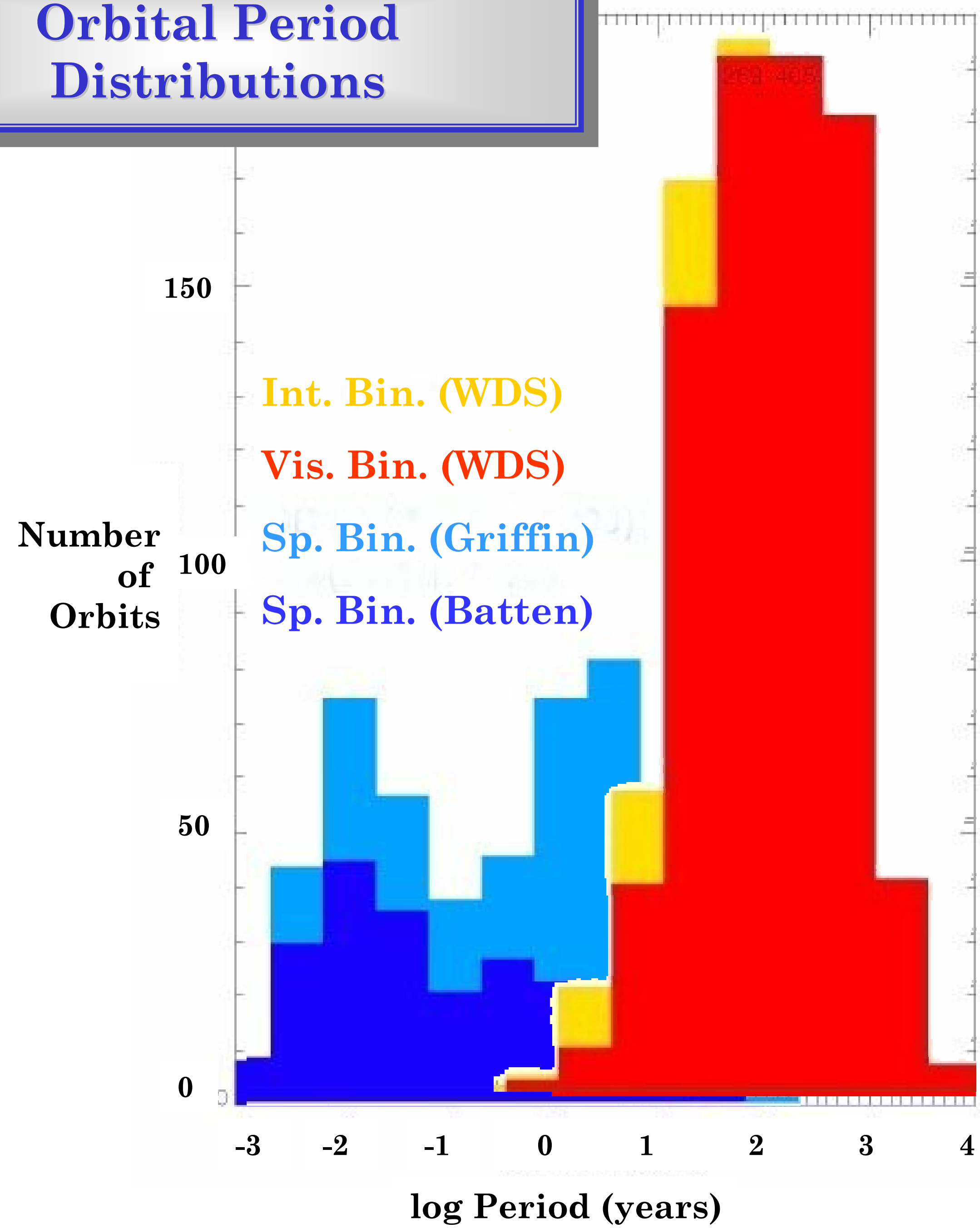
RESOLVED SB2
Yields M_1, M_2, d, L_1, and L_2

Interferometry will clean up here!

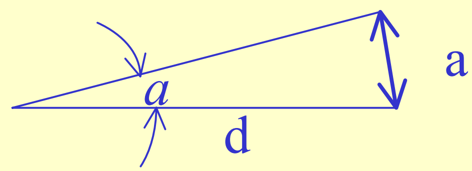
RESOLVED SB1 + PARALLAX
Yields M_1, M_2, L_1, and L_2

Another happy hunting ground for interferometry!

Orbital Period Distributions



Orbital Parallax



Combine the <u>angular semi-major axis</u> and <u>orbital inclination</u>

for a <u>resolved binary</u>

with the <u>linear a Sin I</u>

for a <u>double-lined spectroscopic binary:</u>

$$d_{orbital} = \{\underbrace{(a_1 + a_2)\ \mathrm{Sin}\ i}_{\text{DSB}}\} \,/\, (\alpha\ \mathrm{Sin}\ i)$$

VB

Interferometrically Resolvable SBs

Lower limit to period for a 350 meter baseline

Distance (pc)	$P_{shortest}(M_t=2M_{sun})$	$P_{shortest}(M_t=5M_{sun})$	$P_{shortest}(M_t=10M_{sun})$	$P_{shortest}(M_t=20M_{sun})$
25.0	0.2	0.3	0.4	0.6
50.0	0.5	0.8	1.2	1.6
75.0	0.9	1.5	2.1	3.0
100.0	1.5	2.3	3.3	4.6
125.0	2.0	3.2	4.6	6.5
150.0	2.7	4.2	6.0	8.5
175.0	3.4	5.4	7.6	10.7
200.0	4.1	6.5	9.2	13.1
225.0	4.9	7.8	11.0	15.6
250.0	5.8	9.1	12.9	18.3
275.0	6.7	10.5	14.9	21.1
300.0	7.6	12.0	17.0	24.0
325.0	8.6	13.5	19.2	27.1
350.0	9.6	15.1	21.4	30.3
375.0	10.6	16.8	23.7	33.6
400.0	11.7	18.5	26.2	37.0
425.0	12.8	20.3	28.6	40.5
450.0	14.0	22.1	31.2	44.1
475.0	15.1	23.9	33.9	47.9
500.0	16.3	25.9	36.6	51.7
750.0	30.0	47.5	67.2	95.0
1000.0	46.2	73.1	103.4	146.2
10000.0	1462.3	2312.1	3269.8	4624.2

The Mass-Luminosity Relation

Discovered empirically in 1923 by Hertzsprung and Russell and shortly thereafter described theoretically by Eddington as:

$$L = M^{k} R^{x} \mu^{y} \simeq M^{4} R^{-1/2} \mu^{15/2} \sim M^{k}$$

or

$$M_{bol} = M_o - 2.5\,\kappa \log M$$

The empirical relation has two segments roughly connecting at $M = 0.5M_{sun}$ approximately described by:

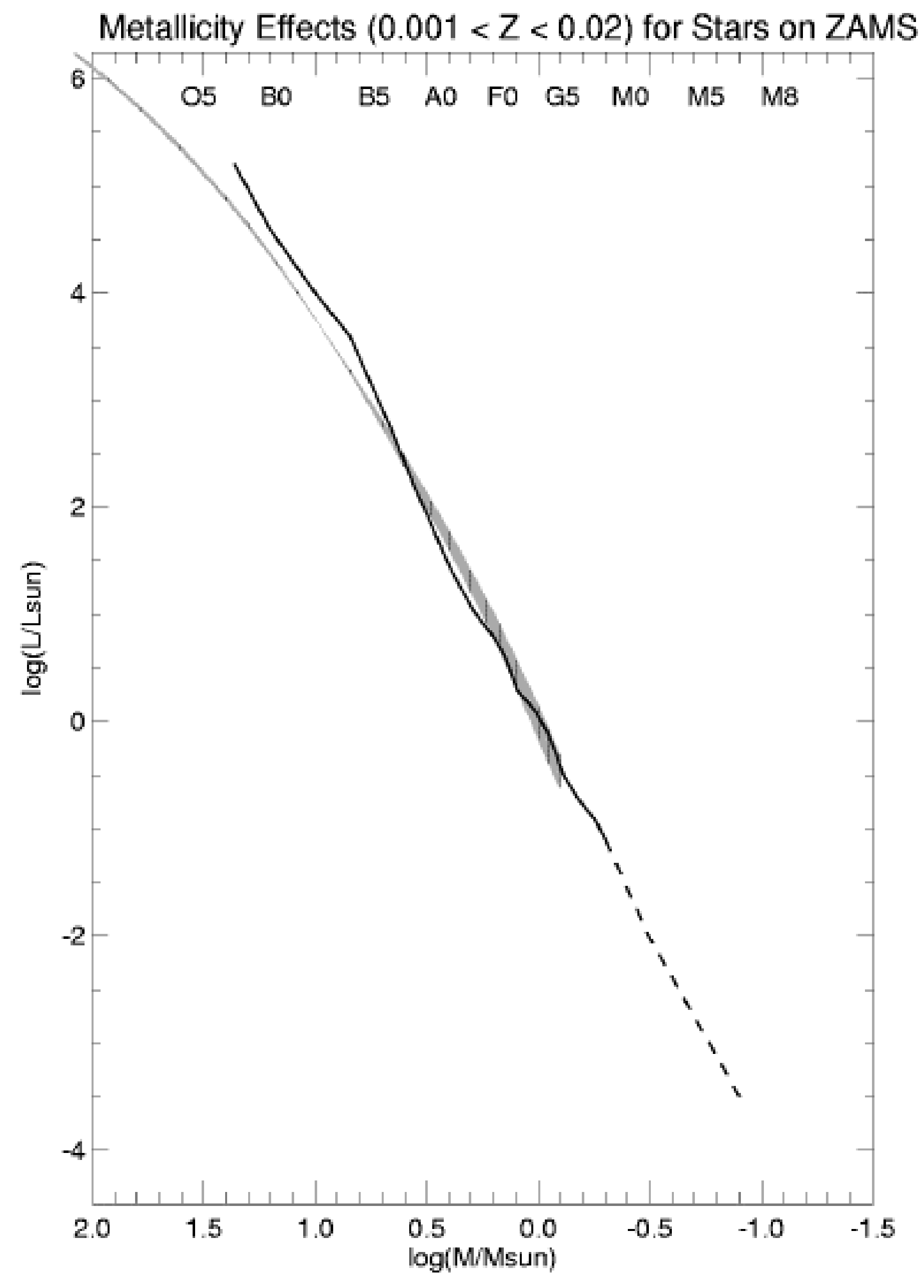
for $M < 0.5M_{sun}$: $\log L/L_{sun} = 2.4 \log M - 0.4$

and for $M > 0.5M_{sun}$: $\log L/L_{sun} = 3.8 \log M$

Theoretical Mass-Luminosity Relation

Illustrated by W.I. Hartkopf 1999.

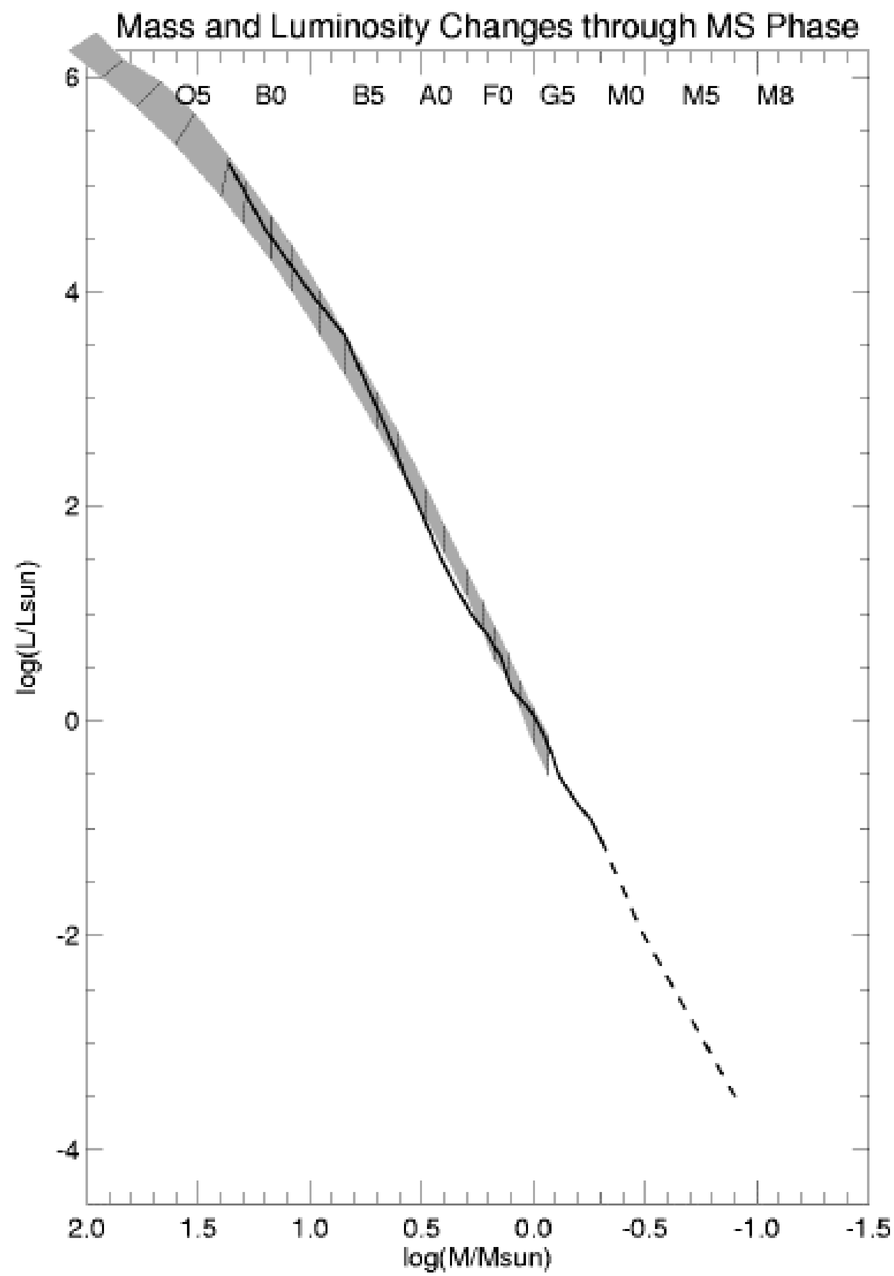
Broadening by Metallicity



Theoretical Mass-Luminosity Relation

Illustrated by W.I. Hartkopf 1999.

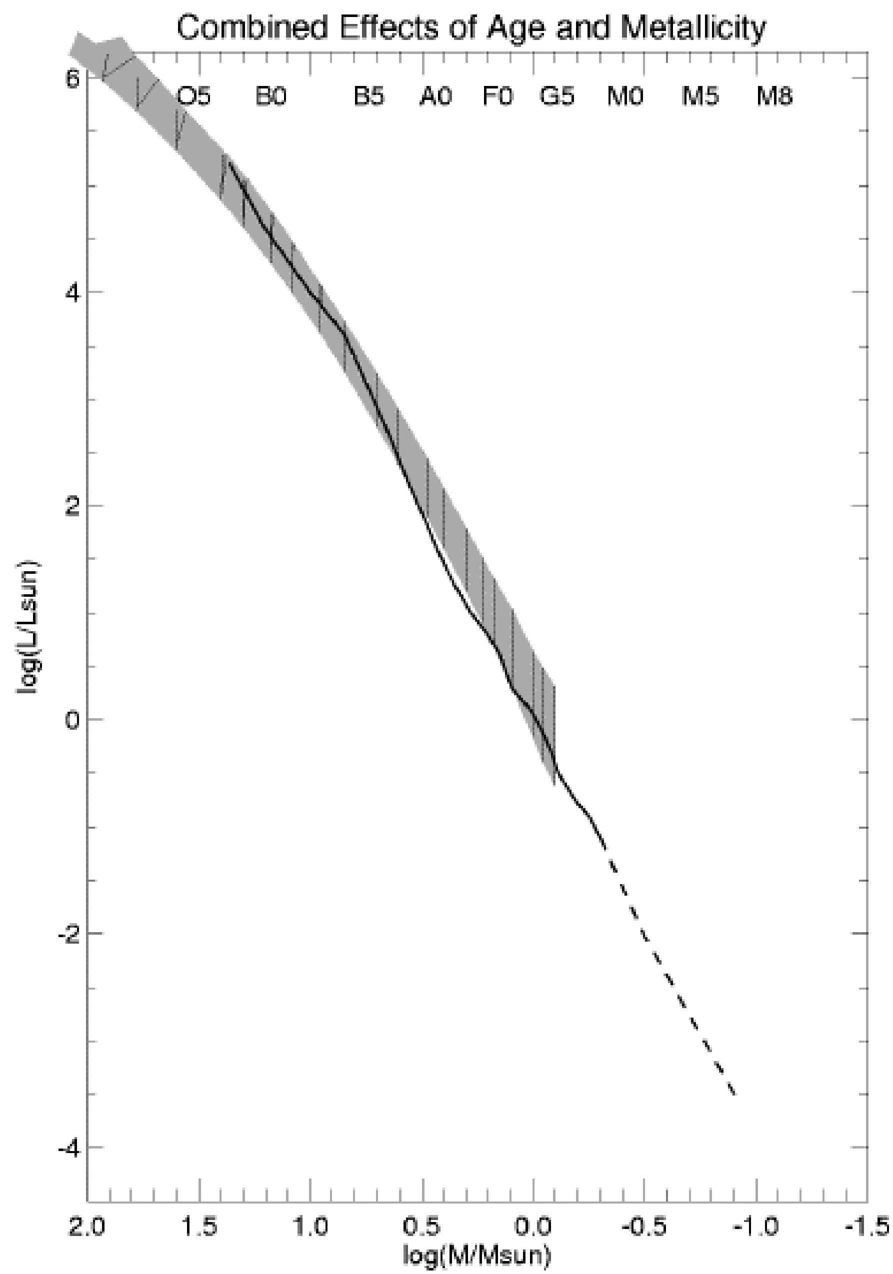
Broadening by Age



Theoretical Mass-Luminosity Relation

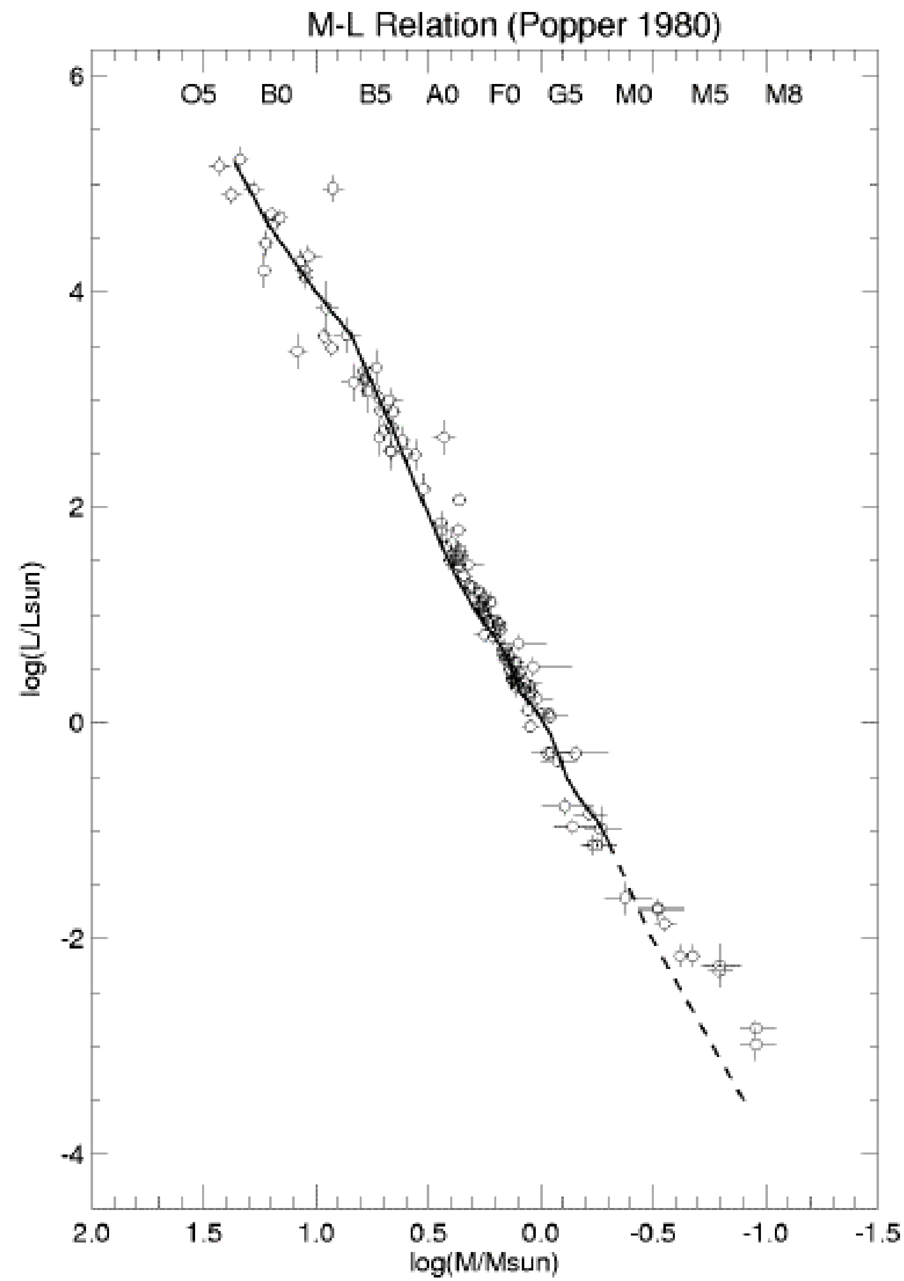
Illustrated by W.I. Hartkopf 1999.

Broadening by Metallicity and Age



Empirical Mass-Luminosity Relation

D.M. Popper. *Ann Rev Astron & Astroph*, **18**, 115, 1980.



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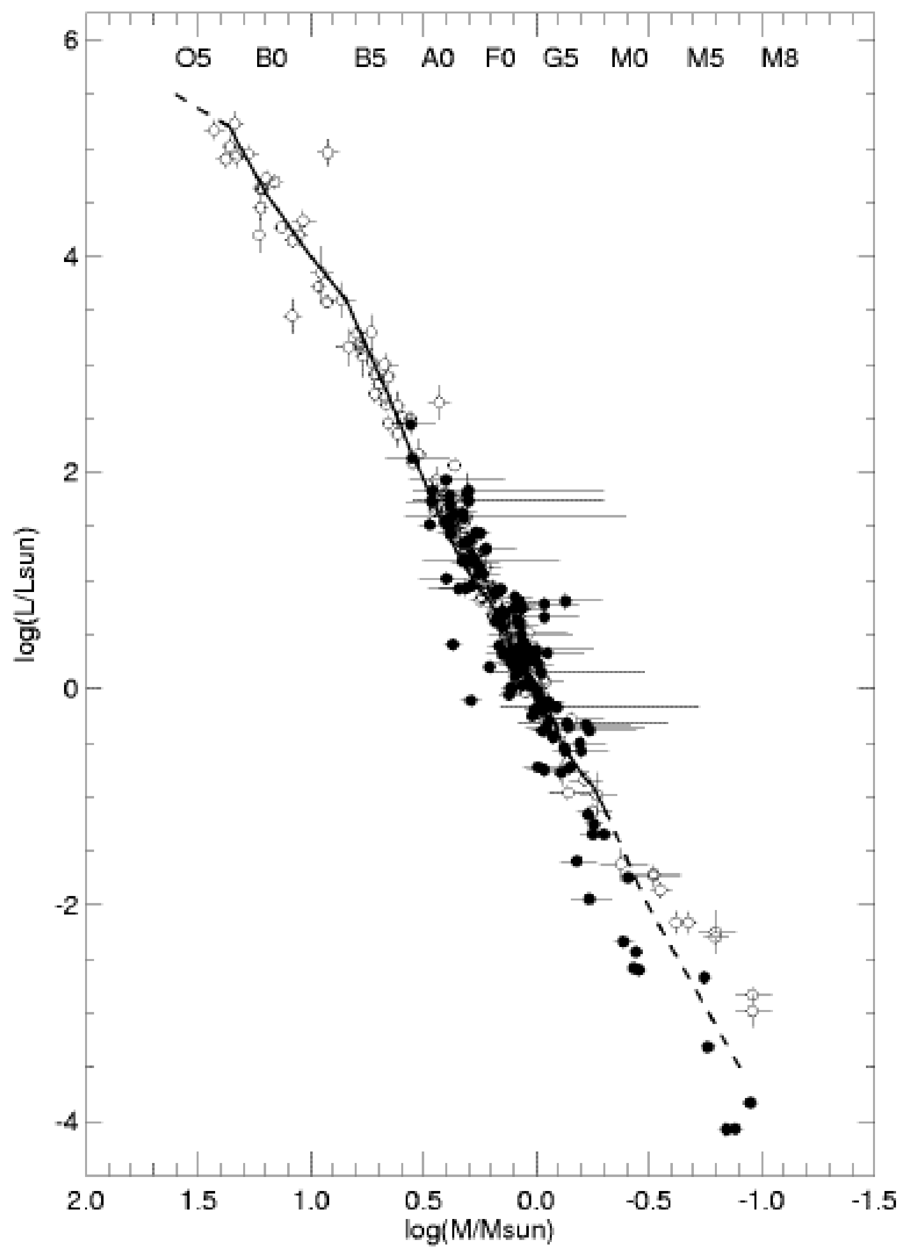

Empirical Mass-Luminosity Relation

D.M. Popper. *Ann Rev Astron & Astroph*, **18**, 115, 1980.

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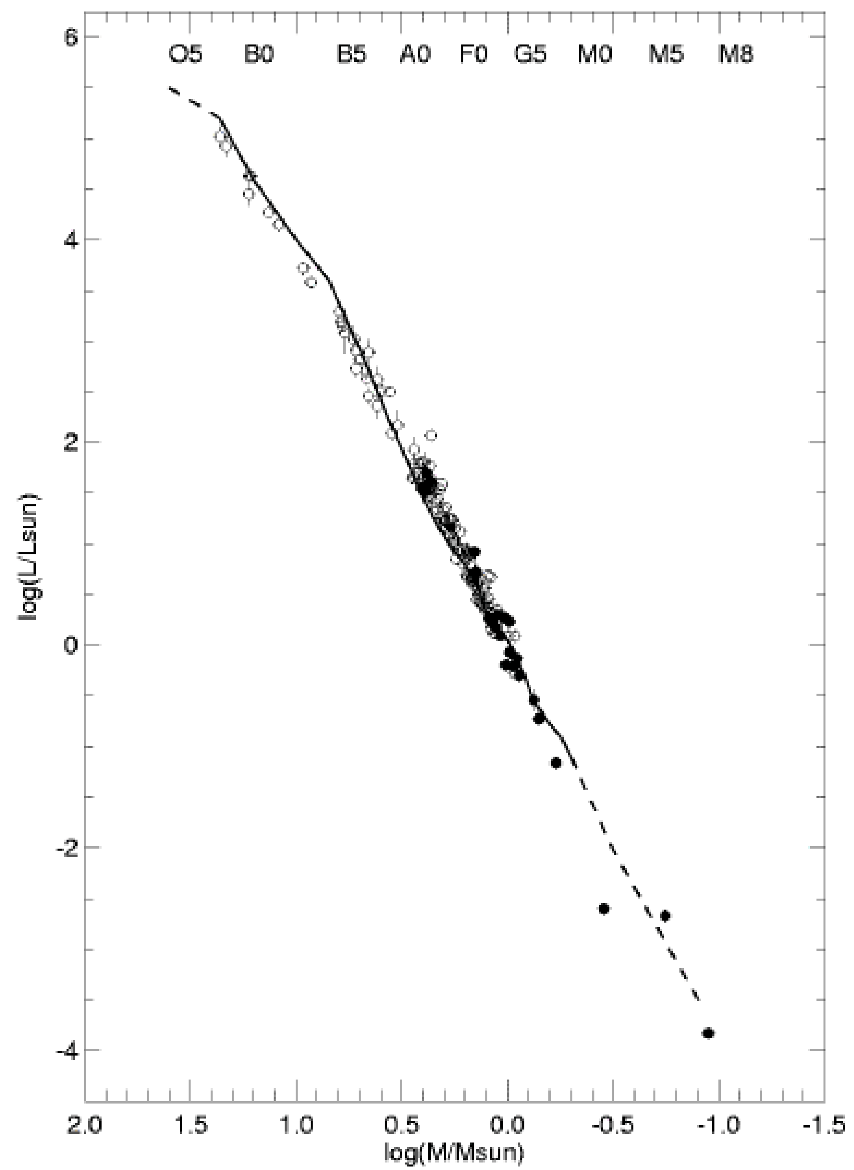

Empirical Mass-Luminosity Relation

D.M. Popper. *Ann Rev Astron & Astroph*, **18**, 115, 1980.

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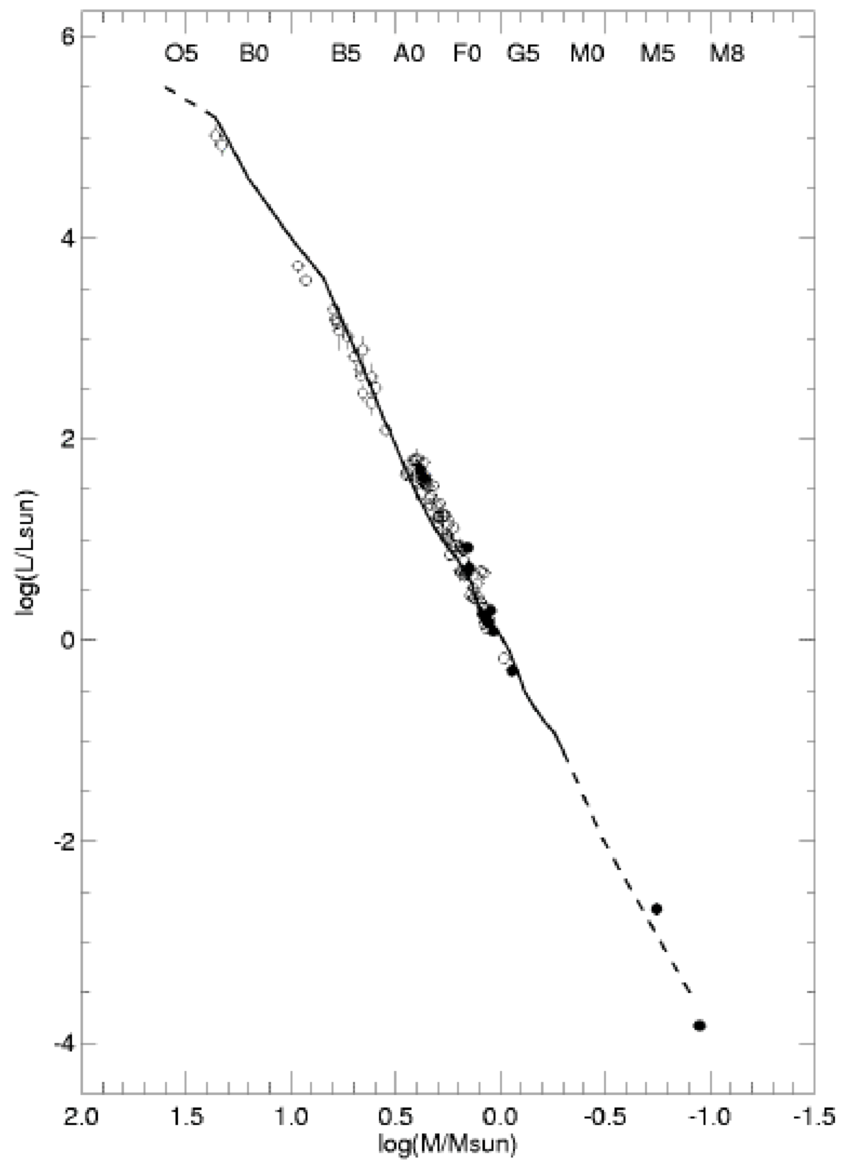

Empirical Mass-Luminosity Relation

D.M. Popper. *Ann Rev Astron & Astroph*, **18**, 115, 1980.

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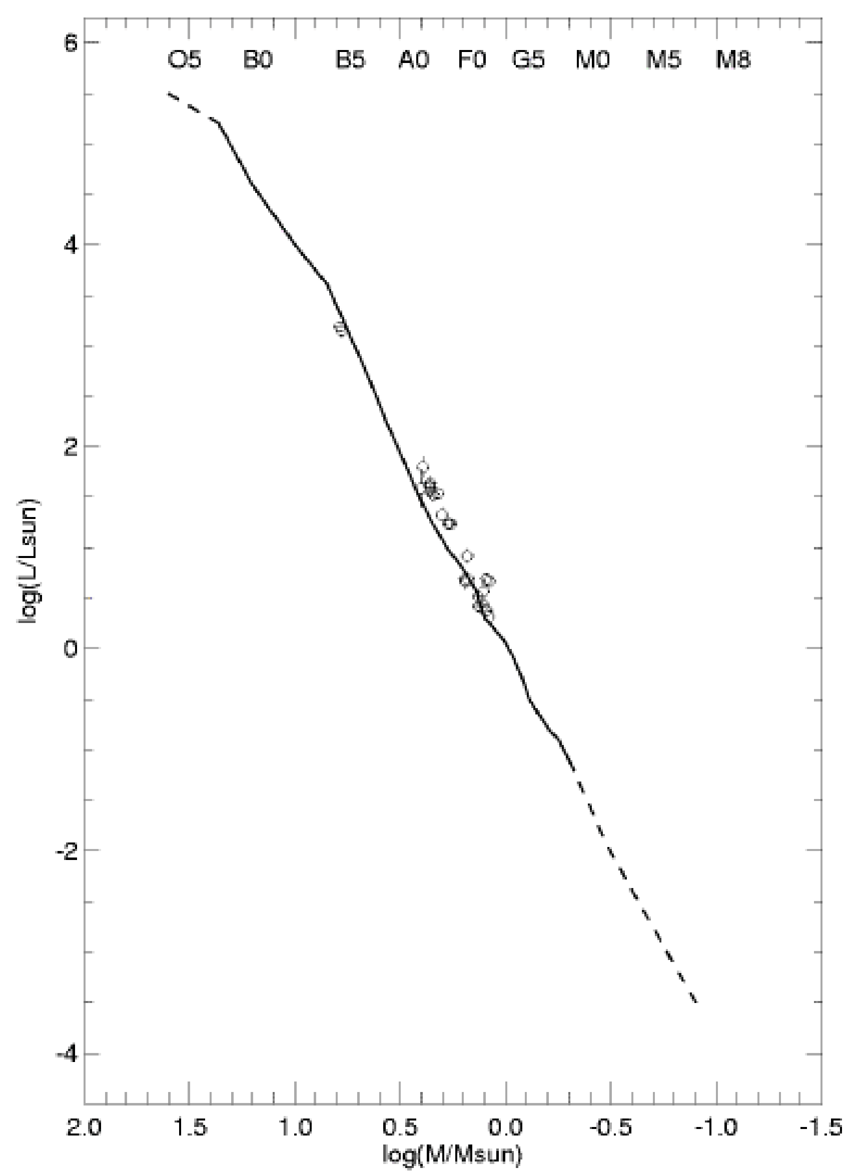

Why Interferometry?

The very high resolution of long-baseline optical interferometry will lead to a very large sample of stars of all spectral types and luminosity classes for which we know the set of parameters

(M, R, L)

with high accuracy.